Evolution of local Ultraluminous mergers from NIR spectroscopy

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Abstract. We present results from our VLT Large Program to study the dynamical evolution of Ultraluminous Infrared Galaxies (ULIRGs) which are the products of mergers of gas-rich galaxies. We have so far obtained near-infrared high-resolution ISAAC spectra of 53 local ULIRGs at several merger timescales and 12 Palomar-Green QSOs (more than half of which are IR-bright sources). We have extracted the stellar velocity dispersion σ and rotational velocity V_{rot} along our slits to derive the kinematics of the merging galaxies. These quantities enable us to answer the following questions about the evolution of ULIRGs: 1) What are the progenitor mass ratios?, 2) How do the stellar kinematics evolve?, and, 3) Is there a connection between ULIRGs and QSOs? We find that the Ultraluminous phase is mainly triggered by mergers of approximately equal mass galaxies, however, less violent minor mergers (of progenitor mass ratio 3:1) also exist in our sample. Dynamical heating of the merging hosts is observed as the stellar systematic rotation decreases with time in favour of the increase of random motions. The merger remnants, being dispersion-dominated systems with non-negligible rotation ($V_{\rm rot}$/sigma ~ 0.6), resemble elliptical galaxies [12]. Placing ULIRGs on the fundamental plane of early-type galaxies [7] shows that they resemble intermediate-mass, disky-isophote-profile ellipticals. After the nuclear coalescence, the black hole masses of ULIRGs, calculated from their relation to the host dispersions, are of the order 10^7 - $10^8\,{\rm M}_\odot$, thus, they do not resemble the supermassive BHs found in local QSOs that are selected to be radio loud (or to have radio loud counterparts [9]). To investigate whether ULIRGs go through a QSO phase during their evolution, we perform a similar (preliminary) analysis of the kinematics of our sample's IR-bright QSOs. We find that the average dispersion of the IR-bright QSOs is similar to that of the ULIRG remnants, indicating that evolutionary links between the two populations may exist. We intend to expand our study and obtain further spectra of optically selected (IR-weak) sources in the future.

1 Introduction

Galaxy mergers, the frequency of which increases with redshift [14], are considered a key mechanism in driving galactic evolution. In the local Universe, the best laboratories for studying violent merging events (believed to be the probable analogs to high-redshift mergers) are the ultraluminous infrared galaxies (ULIRGs). A plethora of numerical models [17],[24] and observations [21], [15] indicates that the ULIRG phase can occur after the first encounter of the galaxies and can be present after their nuclei coalesce, before complete relaxation sets in.

Several studies indicate that ULIRGs transform gas-rich disks into moderate mass ellipticals through merger induced dissipative collapse [17], [16]. The structural parameters of a sample of ULIRGs that have 60 μm flux greater than 1 Jy have been analyzed by Kim et al. (2002) and Veilleux et al. (2002), who found that most of the sources (73%) are well-fit by an elliptical-like r$^{1/4}$ light profile. Similar findings on the near-infrared (NIR) light distribution of ULIRGs was reported by Scoville et al. (2000). While the end products of galactic mergers are largely understood, the physical details of the merging process (such as the evolution of the host properties and the black hole growth) are still very uncertain, even in the local Universe. It is not known, for example, whether ULIRGs (which have a luminosity output $> 10^{12} L_\odot$, comparable to that of QSOS) may go through a QSO phase after the nuclear coalescence.

2 Observations

One way to investigate the physical details and the evolution of ULIRGs is to determine the kinematic and structural properties of the merging (or interacting) galaxies in different merger phases. We are hence conducting an ESO VLT Large Programme (LP; ID 171.B-0442) that traces, through NIR spectroscopy, the host dynamics of a sample of ULIRGs spanning a wide range of merger phase and infrared (IR) luminosity. We have obtained high-resolution, H- and K- band ISAAC spectroscopic data. Including sources from our previous work [12],[25] we have now observed a total of 53 ULIRGS: 29 of those are merger remnants, 23 are (binary) progenitors, and 1 (IRAS 00199-7426) may be a multiple-interaction system [8]. To investigate whether ULIRGs go through a
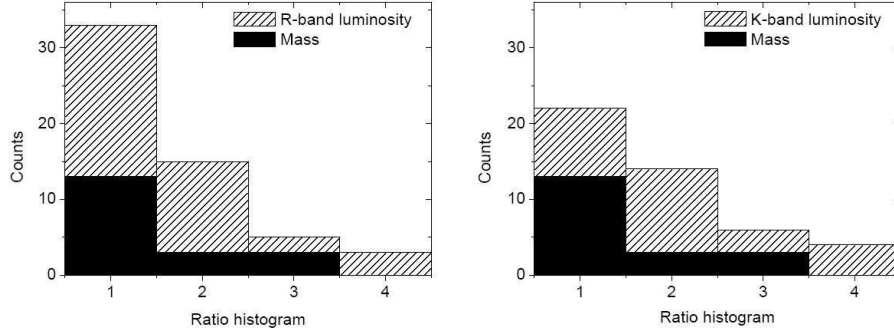
Figure 1: Mass and luminosity ratio histogram. In filled bars we show the mass ratio of the ULIRGs in our sample, measured from the stellar kinematics. In shaded we show the R-band (left panel) and the K-band (right panel) luminosity ratio of the combined 1 Jy and Duc et al. (1997) samples.

QSO phase, we have also acquired ISAAC spectroscopic data for 12 local QSOs, more than half of which are IR bright sources (ratio of integrated IR to big blue bump luminosity > 0.46).

Our on-source integration time varies from 1 to 3 hrs per slit (depending on the redshift of the source, [0.046<z<0.268]), and we use two slits per nucleus, so that we can infer its rotation field. We extract stellar dispersion σ and rotational $V_{\rm rot}$ velocities from the spectra using the Fourier correlation quotient technique [1]; this method provides the line-of-sight (LOS) broadening function with which a stellar template has to be convolved to produce the observed spectrum.

3 Pre-coalescence phase

For the binary (pre-merged) ULIRGs of our sample we are able to derive the kinematics of the individual progenitors. That allows us to investigate the conditions that are needed to trigger an ultraluminous burst during a merger of gas-rich galaxies.

Using the stellar dispersion and, when possible, the stellar rotational velocity, we calculate the mass ratio of the merging galaxies. The average mass ratio of the binary ULIRGs is 1.5:1, while 68% of these sources are 1:1 encounters [4]. This implies that ultraluminous luminosities are mainly generated by almost equal-mass mergers. This result is in agreement with the luminosity ratios calculated for the 1 Jy sample sources [15]. In Fig. 1 we present a histogram of the merging galaxies' mass (filled bars) and luminosity (shaded bars) ratios. The luminosity ratio distribution is different when measured in the R band (left panel) than in the K band (right panel) due to stellar population and dust extinction effects. While the overall mass and luminosity ratio distributions (reasonably) agree, luminosity and mass ratios of individual sources may deviate. In these cases the mass ratio is the most robust result because it is less affected by dust extinction and population effects.

We note, however, that we may be undersampling the unequal-mass merger categories due to dynamical heating (mainly of the smaller companion) and projection effects. We investigate these effects by running merger simulations presented in Naab et al. (2003), after adding gas (equal to 10% of the stellar mass). We then follow the stellar dispersion as a function of time. We find no significant deviations between the apparent and the actual mass ratio of 1:1 mergers, while 3:1 mergers may be observed as 2:1 on small nuclear separations. Thus, it is likely that only a small fraction of our sample have higher mass ratio than measured.

We can also calculate the sense of rotation of each progenitor using the (projected) rotational velocity and assuming that the tidal tails are trailing (whenever archival imaging data allow us to do so). We find that both the counter-rotating and the less violent, co-rotating, merger geometries may lead to ultraluminous activity.

4 Post-coalescence phase

The stellar motions of the coalesced ULIRGs are characterized by an average velocity dispersion of 157 $\rm km\,s^{-1}$ and a projected rotational velocity of 50 $\rm km\,s^{-1}$. The velocity dispersion of the late-phase is greater than that of the early-phase ULIRGs (142 $\rm km\,s^{-1}$), which reflects a part of the dynamical heating that the merging systems undergo.
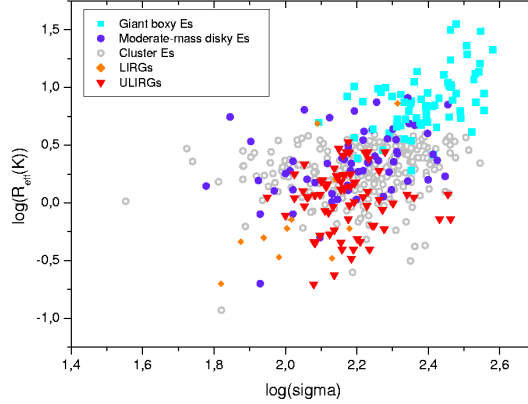
Figure 2: The early-type galaxies fundamental plane (R-σ projection). The giant boxy and intermediate-mass disky Es data are taken from Bender et al. (1992) and Faber et al. (1997). More (cluster) Es are from Pahre (1999) and LIRGs from Shier & Firscher (1998) and James et al. (1999).

When correcting the rotational velocity of the coalesced ULIRGs for inclination effects (by using an average inclination equal to that of spirals in the field), we find that the $V_{\rm rot}/\sigma$ ratio is 0.64. The ULIRG remnants are, thus, dispersion supported systems, where rotation is still non-negligible, resembling ellipticals (Es). To investigate what type of Es can be formed by ultraluminous mergers, Genzel et al. (2001) and Tacconi et al. (2002) acquired similar high-resolution NIR spectroscopic data for a smaller sample of mostly late merger-stage ULIRGs. By placing their sources on the fundamental plane (FP) of early-type galaxies [7], Tacconi et al. (2002) found indications that ULIRGs resemble intermediate mass ellipticals/lenticulars with disky isophotal profiles. From our data we can plot the R-σ projection of the plane (see Fig. 2) for the sources included in our sample. Giant (boxy) Es are shown in boxes, moderate-mass (disky) Es in filled circles, and further cluster Es in open cirles. Some luminous infrared galaxies (LIRGs; $10^{11}L_\odot < L < 10^{12}L_\odot$) are presented in diamonds and the ULIRGs of this study in triangles. The fact that ULIRGs clearly populate the intermediate mass ($\sim 10^{11}$ $M_\odot$) Es part of the FP suggests that these two populations are linked, while giant Es probably have a different formation history.

5   Implications on the BH growth

Knowing the stellar dispersion, we can calculate the BH mass, M_{BH}, with the aid of the $M_{BH} - \sigma$ relation (as presented in Tremaine et al. 2002; $M_{BH} = 1.35 \times 10^8 [\sigma/200]^{4.02}$ M$_\odot$, where σ is in km s^{-1}). While the $\mathrm{M_{BH}} - \sigma$ relation is valid for virialized systems, it can still be applied to the post-merger ULIRGs. By the time the two nuclei have coalesced, the host kinematics have practically reached their relaxation values [3]. The recent simulations by Di Matteo et al. (2005) also indicate that merger remnants follow this relation. Its application leads to a median remnant black hole mass of 8×10^7 M$_\odot$.

On the other hand, the $\mathrm{M_{BH}} - \sigma$ relation needs to be proven valid during the merger before it can be applied to the dynamically perturbed, non-virialized early-phase ULIRGs. Simulations of gas-rich mergers that we ran (see Sect. 3) show that by the time the merger has advanced to the ULIRG phase, the scatter around the $\mathrm{M_{BH}} - \sigma$ relation is small (suggesting that the relation can be used). However, these simulations (like those of Di Matteo et al. 2005) assume that the amount of gas that accretes onto the black hole from the central resolution element of the simulation (denoted as efficiency ϵ) is constant. The latter is known to vary drastically when the AGN is switched on/off. Consequently, any early-phase ULIRG black hole properties derived with the aid of the $\mathrm{M_{BH}} - \sigma$ relation are carrying this uncertainty.

We can calculate the Eddington efficiency $\eta_{\rm Edd}$, the ratio between the Eddington and the dynamical $\mathrm{M_{BH}}$, by assigning 50% of the IR luminosity to the AGN. Statistically, this assumption is reasonable given that some ULIRGs are largely starburst- while others are AGN- powered [11]. For individual cases, though, it may make some sources seem to accrete at super-Eddington rates; in these cases we assign $\eta_{\rm Edd}$=1. The Eddington efficiency of the ULIRG remnants is on average 0.52 and it is higher than that of the progenitors (see Fig. 3).

Photometric study of the 1 Jy sample by Veilleux et al. (2002) indicated that the nuclear contribution to the IR luminosity is on average greater for the single than for the binary ULIRGs. Thus, the average
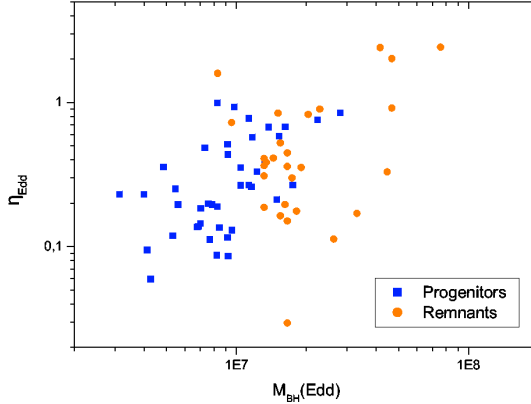
Figure 3: The Eddington efficiency vs the Eddington BH mass of the pre- and post- coalescence sources.

remnant accretion rate we calculated is only a lower limit of its actual value. Such high η_{Edd} values may be an observational confirmation of the predictions of Springel et al. (2005) and Di Matteo et al. (2005). These authors suggest that after the nuclear coalescence, the gas infall to the center of the system is so high that the AGN may even accrete at rates close to Eddington.

6 Discussion: Are there evolutionary links between ULIRGs and QSOs?

A late-merger evolutionary scenario (originally based on Sanders et al. 1988) suggests that after the coalescence, the IR emission arising from the starburst and the nuclear dust is so strong that the remnant reaches QSO-like luminosities. However, as the dust clears out from the nuclear region due to AGN winds and supernova feedback, the system goes through an optically bright phase, before further accretion is prevented [24].

For the IR-bright sources of our sample reduced thus far, we find that the average dispersion is similar to that of the ULIRG remnants. Thus, their black hole and host masses are also of comparable size (10^7-10^8 and 10^{10}- 10^{11} M$_\odot$ respectively). The Eddington efficiencies of these QSOs are high (~ 0.5). Furthermore, the recent HST NICMOS imaging analysis of local ULIRGs and IR bright QSOs [28] indicates that their hosts have similar NIR colours.

The IR bright QSOs seem to differ from local QSOs that host supermassive black holes, such as the radio-loud (RL) sources or their radio-quiet optical counterparts (RQC) of Dunlop et al. (2003). The RL/RQC QSOs have black holes of the order 10^8 and 10^9 M$_\odot$ that accrete on average at ~ 0.05 of the Eddington rate, and that are located in 5 times more massive and luminous (K-band) hosts. Probably the radio selected QSOs have a different formation history than the IR bright ones.

Our preliminary results seem to indicate evolutionary links between ULIRGs and IR bright QSOs; however, the fact that some IR QSOs have prominent spiral hosts implies that they may have a minor-merger origin. We need to improve our statistics and to enrich our sample with optically selected QSOs in order to derive conclusions about the optically bright phase of this scenario.

7 Conclusions

We have acquired spectroscopic H-band, long-slit data of 53 ULIRGs (at a variety of merger timescales) and 12 PG QSOs to trace the evolution of their dynamical properties. We find that:

1. The mass ratio of the binary sources indicates that ULIRGs mainly originate from 1:1 and 2:1 mergers. However, less violent events like unequal-mass mergers (and possibly co-rotating orientations) are also capable of triggering an ultraluminous phase.

2. Loss of systematic rotation in favor of increase of random motions is observed from the analysis of the stellar kinematics. The average stellar dispersion for the fully merged sources equals 157 km s^{-1}.

3. The ultraluminous merger will mainly lead to the formation of moderate mass ellipticals, similar to those with disky isophotes.

4. Using the $M_{BH} - \sigma$ relation we find that the average M_{BH} of the already coalesced ULIRGs is of the order 10^7-10^8 $M_\odot$.

5. The Eddington efficiency increases from the pre- to the post- merger sources. The value of the increase is uncertain due to the application of the $M_{BH} - \sigma$ relation for the early-phase (non-virialized) ULIRGs and due to the increase of the nuclear luminosity with time. The high efficiency of the remnants can be realistic (and attributed to the increase of material falling onto the BH).

6. The IR bright QSO dispersions and black hole masses, being of the order 10^7-10^8 $M_\odot$, resemble those of ULIRG remnants, indicating a possible link between the two populations. However, they differ from radio-selected sources that host supermassive black holes of low accretion rates.

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